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This is the Accepted version of the following publication

Debnath, Ashim, Blackman, R and Haworth, N (2014) A Tobit model for analyzing speed limit compliance in work zones. *Safety Science*, 70. 367 - 377. ISSN 0925-7535

The publisher's official version can be found at
<http://www.sciencedirect.com/science/article/pii/S0925753514001714>
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Cite this article as:

Debnath, A.K., Blackman, R., and Haworth, N. (2014) A Tobit model for analyzing speed limit compliance in work zones. *Safety Science*, Vol. 70, pp. 367-377.

A TOBIT MODEL FOR ANALYZING SPEED LIMIT COMPLIANCE IN WORK ZONES

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ABSTRACT

Poor compliance with speed limits is a serious safety concern in work zones. Most studies of work zone speeds have focused on descriptive analyses and statistical testing without systematically capturing the effects of vehicle and traffic characteristics. Consequently, little is known about how the characteristics of surrounding traffic and platoons influence speeds. This paper develops a Tobit regression technique for innovatively modeling the probability and the magnitude of non-compliance with speed limits at various locations in work zones. Speed data is transformed into two groups—continuous for non-compliant and left-censored for compliant drivers—to model in a Tobit model framework. The modeling technique is illustrated using speed data from three long-term highway work zones in Queensland, Australia. Consistent and plausible model estimates across the three work zones support the appropriateness and validity of the technique. The results show that the probability and magnitude of speeding was higher for leaders of platoons with larger front gaps, during late afternoon and early morning, when traffic volumes were higher, and when higher proportions

of surrounding vehicles were non-compliant. Light vehicles and their followers were also more likely to speed than others. Speeding was more common and greater in magnitude upstream than in the activity area, with higher compliance rates close to the end of the activity area and close to stop/slow traffic controllers. The modeling technique and results have great potential to assist in deployment of appropriate countermeasures by better identifying the traffic characteristics associated with speeding and the locations of lower compliance.

Keywords: work zone safety, Tobit regression, roadworks, speeding, speed limit.

1. INTRODUCTION

Excessive and differential speeds are major contributing factors in work zone crashes and driver compliance with work zone speed limits is generally poor (Allpress and Leland Jr, 2010; Garber and Zhao, 2002). Speeding was cited as a contributing factor in 42% of work zone crashes in Texas (Brewer et al., 2006), 7% of fatal crashes in Georgia (Daniel et al., 2000), and 25% and 16% of fatal and injury crashes respectively in Kansas (Bai and Li, 2011). As well as increasing crash risk, exceeding work zone speed limits also increases the severity of crashes when they occur. These points apply almost universally to highway work zones regardless of their location and characteristics, as demonstrated in a large number of studies worldwide (Allpress and Leland Jr, 2010; Brewer et al., 2006; Hajbabaie et al., 2011a; Haworth et al., 2002; Li and Bai, 2008; Meng et al., 2010).

Despite the numerous studies of work zone speed characteristics and evaluations of safety treatments, two key gaps remain in current knowledge about work zone speed limit compliance. First, there is no comprehensive technique for modeling both the probability and magnitude of speed limit compliance in work zones. Most studies have analyzed magnitude of compliance using basic inferential statistics of speed and speed limit compliance. However, to better identify the speeders, speeding prone locations, and traffic characteristics related to speeding, it is necessary to develop an appropriate regression modeling technique which is able to model both the probability and the magnitude of non-compliance. Second, most analyses of work zone speeds have not accounted for the effects of vehicle and traffic characteristics on compliance levels, arguably because of not using regression techniques in their analyses. As a result, little is known about how the characteristics of surrounding traffic and the presence of platoons influence speeds in work zones.

This paper aims to address the two key gaps in literature by developing an innovative technique for modeling both the probability and magnitude of speed limit compliance in work zones while controlling for the effects of different vehicle and traffic related factors. The resulting Tobit regression model is illustrated using speed data collected from multiple points in three long-term work zones in Queensland, Australia. The robustness of the technique is demonstrated by calibrating the model with data from different traffic conditions of the three work zones. The modeling technique is the key contribution of this paper, while the findings have great potential to assist in development and evaluation of appropriate speed reduction measures by better identifying high-risk speeders, locations of speeding, and traffic conditions related to high-risk speeding.

2. LITERATURE REVIEW OF WORK ZONE SPEED MODELING TECHNIQUES

Many studies have analyzed travel speeds in work zones to both understand the baseline speed characteristics and to evaluate the speed reduction potential of countermeasures. For example, Bham and Mohammadi (2011) examined baseline free-flow speeds and compliance levels of car and trucks in four Missouri work zones using descriptive statistics and *t*-tests. In an older Illinois study, Benekahal et al. (1992) used descriptive statistics of speeds and speed limit compliance to group the behavior of drivers into four distinct categories: (1) considerable speed reductions after passing the first speed reduction sign (63% of drivers), (2) reduced speeds close to the actual work location (11% of drivers), (3) unchanged travel speeds (11% of drivers), and (4) no significant pattern (15% of drivers).

A range of analysis techniques have been used to evaluate the effectiveness of speed control measures in work zones (see Debnath et al., 2012 for a review of related literature). In an evaluation study of perceptual countermeasures using traffic cones, Allpress and Leland Jr (2010) analyzed before and after free flow speeds at three points in a New Zealand highway work zone using one-way ANOVA and Tukey's Honestly Significant Difference post hoc tests (HSD) without distinguishing between vehicle types. Bai and Li (2011) analyzed the speeds of the first two vehicles in a traffic queue using ANOVA and two-sample *t*-tests to measure the speed reductions associated with using an Emergency Flasher Traffic Control Device. The effects of police and photo-radar enforcement in two Illinois work zones were examined using *t*-tests, Chi Square, Kolmogorov-Smirnov tests, and Least Significant Difference tests (Benekahal et al., 2010). Temporal and spatial effects of the measures were evaluated using two indicators: mean speed and degree of speeding (at four levels: percentage of vehicles exceeding speed limits, exceeding up to 5 mph, exceeding by 5-10 mph, and exceeding by more than 10 mph) for each vehicle type. Bai et al. (2010) analyzed speed reductions in response to temporary signage in two Kansas highway work zones using descriptive statistics of speed change and ANOVA tests. Brewer et al. (2006) analyzed speed data collected from six points in two Texas highway work zones using mean, 85th percentile, and standard deviation of speed, and percentage of compliant vehicles. Wang et al. (2003) also analyzed speed data from three Georgia work zones using *t*-test, Bartlett's test, ANOVA, and Tukey's HSD test.

The foregoing review shows that most studies of work zone speeds have presented statistical summaries and basic inferential statistics of speed and speed limit compliance data without examining the effects of many potential influencing factors. Travel speeds do not necessarily depend only on a single factor (e.g., day/night, type of vehicle), but are likely to be influenced by characteristics of vehicles and their surrounding traffic as well. Several studies (e.g., Bai et al., 2010; Benekahal et al., 1992; Benekahal et al., 2010; Debnath et al., 2014) have demonstrated that travel speeds of cars differ from those of trucks. In addition, Morgan et al. (2010) found that the presence of a lead vehicle has significant effects on follower vehicles' speeds. An evaluation of pilot car operation (Debnath et al., 2014) reported that travel speeds vary according to traffic volumes, gaps from lead vehicles, time of day, and proportions of medium and heavy vehicles. Findings from these studies indicate that the effects of vehicular and traffic characteristics need to be accounted for in order to comprehensively model travel speeds and speed limit compliance in work zones.

In the study by Debnath et al. (2014), the probability of speed limit non-compliance was estimated using a binary logistic model, which categorizes individual speed observations into two groups: compliant (at or below the posted limit) and non-compliant (above the limit).

While this modeling approach can account for the effects of vehicular and traffic characteristics on speed limit non-compliance, the magnitude of non-compliance is not captured in the model. Specifically, the model does not differentiate between the non-compliant drivers exceeding speed limits by a large amount and those exceeding by a small amount. Since an increase in speed increases the likelihood of a crash and the severity of a crash when it occurs (Aarts and van Schagen, 2006; Meng et al., 2010), it is important to account for both the probability and magnitude of non-compliance with speed limits in safety analyses.

3. STATISTICAL MODELING METHOD

To examine how different characteristics of vehicles and their surrounding traffic affect driver speeds, it is necessary to use appropriate regression models. In addition, as discussed earlier, from a safety perspective it is important to account for both the probability and the magnitude of non-compliance with speed limits in speed data modeling. A possible way of modeling this problem is transforming the speed values to ‘excess speed’ (i.e., measured speed – speed limit) which would give positive values for the non-compliant drivers and negative or zero values for the compliant drivers. The non-compliant drivers are of key concern in terms of safety improvement in work zones. However, to understand the degree of non-compliance, it is necessary to analyze the speed profiles of the compliant drivers as well.

A Tobit regression model (Tobin, 1958) which models dependent variables with censored data is an appropriate technique for modeling the excess speed data. In the Tobit model framework, the observations of compliant drivers can be clustered at a threshold value of zero (which is termed as left censored in standard Tobit model literature) and those of non-compliant drivers can be kept as continuous data to represent the magnitude of non-compliance.

The Tobit model can be expressed as (for speed observation i)

$$Y_i^* = \beta X_i + \varepsilon_i, \quad i = 1, 2, \dots, N \quad (1)$$

$$Y_i = Y_i^* \text{ if } Y_i^* > 0 \quad (2)$$

$$Y_i = 0 \text{ if } Y_i^* \leq 0 \quad (3)$$

Where Y_i is the dependent variable (speed above the posted limit) which is measured using a latent variable Y_i^* for positive values and censored otherwise, β is a vector of estimable parameters, X_i is a vector of explanatory variables, ε_i is a normally and independently distributed error term with zero mean and constant variance σ^2 , and N is the number of observations. A detailed description of the Tobit model can be found in Washington et al. (2011).

To estimate the marginal effects of the independent variables, the change in the expected value for cases above zero ($\partial E[Y']/\partial X_k$) and the change in the cumulative probability of being above zero ($\partial F(z)/\partial X_k$) for a specific independent variable X_k are calculated using the following expressions (removing the subscript i for simplification):

$$\frac{\partial E[Y']}{\partial X_k} = \beta_k \left[1 - z \frac{f(z)}{F(z)} - \frac{f(z)^2}{F(z)^2} \right] \quad (4)$$

$$\frac{\partial F(z)}{\partial X_k} = \beta_k \frac{f(z)}{\sigma} \quad (5)$$

where $E[Y'] = E[Y|Y > 0]$, Y' denotes the non-censored observations (i.e., positive values of excess speed), z is the z -score associated with the area under the normal curve, $F(z)$ is the cumulative normal distribution function, and $f(z)$ is the unit normal density. The changes were obtained by computing the effect of a unit change in a continuous explanatory variable from its mean value or a change from 0 to 1 for a binary variable while keeping all other variables at their means. In case of variables with more than two categories, the changes were computed on the basis of category change from 0 to 1, whereas the other categories of the variable were kept at 0 and all other variables at their means.

Overall goodness of fit of the model is assessed using Maddala Pseudo R^2 (Maddala, 1983) which is expressed as $1 - EXP[2(LL(0) - LL(\beta))/N]$, where $LL(0)$ and $LL(\beta)$ are the log-likelihood at zero and at convergence respectively.

It should be noted that the standard assumptions of a linear regression model apply to a Tobit model. The assumptions include dependent variable to be continuous, linear relationship between dependent variable and independent variables, independently and randomly sampled observations, non-autocorrelated disturbance terms, uncorrelated disturbances and independent variables, approximately normally distributed disturbance terms with zero mean and constant variance.

In the case of censored data, using Ordinary Least Squares (OLS) regression leads to serious specification errors in model structure and yields biased and inconsistent parameter estimates (Washington et al., 2011). This is because unbiasedness and consistency in estimated parameters require the disturbance term to be normally and independently distributed with zero mean and constant variance. An OLS regression also needs to ignore the censoring nature of the dependent variable or exclude the censored data from analysis. To model the censored speed data, as formulated in eq. 1-3, the Tobit regression approach is therefore preferred over the OLS regression.

4. DATA

4.1 Study work zones

Speed and speed limit compliance are likely to vary at different points in work zones. Research shows that drivers change speeds in response to roadway conditions, traffic control devices, and other environmental factors (Benekahal et al., 1992; Allpress and Leland Jr, 2010; Brewer et al., 2006), indicating that it is important to study speed profiles throughout the entire work zone as well as at particular points. However, it is not practical to measure speeds at short intervals due to limited data collection resources and likely minimal variation. The alternative adopted in this study was to measure speeds at multiple points in work zones, determined at least partly by work zone characteristics (e.g., speed reduction signage, activity area).

The current study measured speeds at four points within three long-term work zones (referred to hereafter as Sites 1 - 3) in Queensland, Australia. According to Queensland's MUTCD (Queensland Government, 2010), a long-term work zone is one which requires a traffic guidance scheme to operate both day and night and may be left unattended. Schematic

diagrams of the work zones showing the posted speed limits and the location of the four speed measurement points are presented in Figures 1-3 (drawings not to scale). Standard sets of signage following the Manual of Uniform Traffic Control Devices (MUTCD)¹ used in Queensland (Queensland Government, 2010) were used at all sites. It should be noted that vehicles travel on the left in Australia.

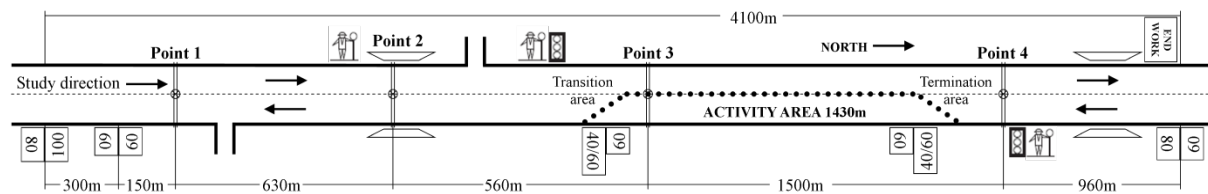


FIGURE 1: Site 1 work zone plan

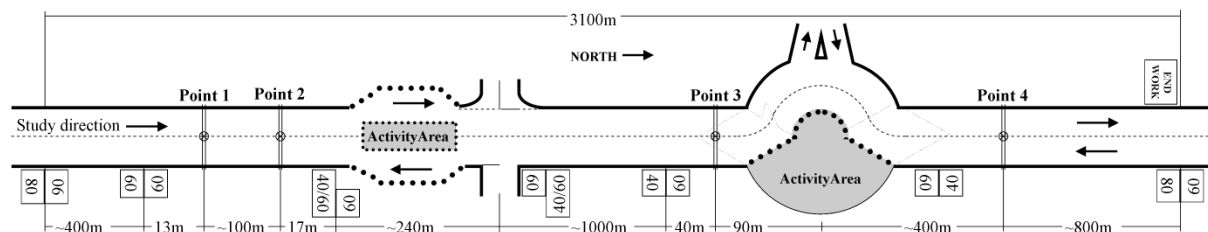


FIGURE 2: Site 2 work zone plan

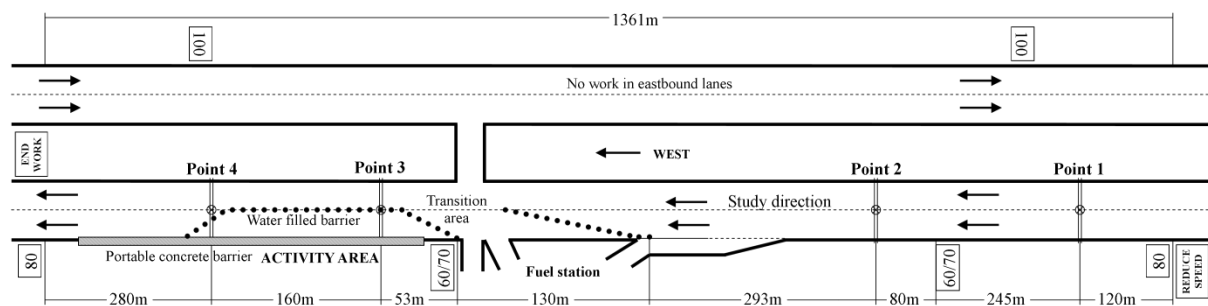


FIGURE 3: Site 3 work zone plan

Site 1 was an undivided sealed two lane road (one lane each way) with pre-work speed limits of 100 km/h (southern end) and 80 km/h (northern end). The 4.1 km road section was straight and mostly flat with good sight distance. Average daily traffic volume was 3,415 vehicles with 74.9% of total traffic observed during daytime hours (6am – 6pm). Work (resurfacing) involved full closure of one lane within the activity area, with the closed lane alternating (southbound/northbound) as required. Traffic controller operated temporary traffic lights (and

¹ The typical components of a work zone in Queensland's MUTCD (Queensland Government, 2010) are termed differently from the FHWA's MUTCD (FHWA, 2009). For example, the terms 'taper area', 'safety buffer', and 'work area' in Queensland correspond to the FHWA's terms 'transition area', 'buffer space', and 'work space' respectively. The terms 'advance warning area' and 'termination area' are similar in both versions of the MUTCD. The term 'activity area' is used in FHWA's MUTCD to represent the work space and buffer space together but a similar term is not used in Queensland's MUTCD.

an additional traffic controller upstream to prevent vehicles queuing on bridge) were used to control traffic at each end of the activity area. Posted speed limit in the activity area was 40 km/h and 60 km/h during work hours (6am-6pm) and no-work hours, respectively.

At Site 2, work involved the addition of an extra lane in each direction to the existing two lanes (one each way). The pre-work speed limits were 90 km/h at the southern end of the work zone and 80 km/h at the northern end. The 3.1 km road section was flat with a mixture of straight sections and minor curves. Average daily traffic volume was 7,584 vehicles, of which 84.1% were observed during daytime hours. The activity area on the roundabout had a 40km/h limit all time, whereas the other activity area has 40 and 60 km/h during work hours and no-work hours respectively. With regard to removal and replacement of the 40/60 km/h signage, the research team could not be assured that the signage was always placed after data collection Point 2 by traffic controllers, as it was in the original plan. Therefore, data from Point 2 were subsequently excluded from analysis.

Site 3 comprised two lanes in each direction, divided by a 15 meter wide median, with 100 km/h pre-work speed limit. Average traffic volume was 11,307 vehicles per day, 79.5% of which were observed during daytime hours. Work involved construction of a new westbound slip lane exiting a fuel station, no traffic interruptions in the eastbound lanes. To allow vehicles exiting the fuel station merging on to through traffic, a second transition area was created after the standard transition area upstream. Field observation by authors showed that the vehicles exiting the fuel station comprised only a very small proportion of the through highway traffic. Therefore, any effects on the speeds of the overall traffic stream were considered negligible. The entire activity area was delineated by a water filled barrier, while the main work area was also protected by a portable concrete barrier. Speed limits in the activity area were changed from 60 km/h to 70 km/h at 6pm, and returned to 60 km/h at 6.30am for start of work day. In addition to the standard MUTCD signage, there was a fixed 'Police Enforcement Zone' sign, situated midway between data collection Points 1 and 2 (no enforcement was carried out during the data collection period).

4.2 Data collection and preparation

Speed data were collected using pairs of pneumatic tubes installed 1 meter apart on the pavement and connected to a MetroCount Vehicle Classification System. Travel speed, headway, gap, type of vehicle, and time were collected for each vehicle traversing the tubes over a continuous period of seven days. Vehicles were classified using the ARX vehicle classification scheme (MetroCount, 2009), which classifies vehicles into three aggregate classes: Light vehicles (Very short – bicycle, motorcycle; Short – sedan, wagon, 4WD, utility, light van; Short towing – trailer, caravan, boat etc.), Medium vehicles (two and three axle bus or truck, four axle truck), and Heavy vehicles (articulated vehicle or rigid vehicle and trailer with more than two axles, B-double or heavy truck and trailer, double or triple road train or heavy truck and more than one trailer). Data were collected and analyzed in metric units.

Individual vehicle data were extracted by running 'Individual vehicle reports' from the Metrocount software. Separate datasets were obtained for each data collection point. A rigorous data cleaning process was undertaken to identify and remove potentially erroneous data points. Firstly, the data points with zero headway, which were reflected in the individual vehicle reports with the label "coerced sequence", were removed. Secondly, the observations where a vehicle was heading in the opposite direction to the direction of interest were

removed. The northbound traffic in Sites 1 and 2 and westbound traffic in Site 3 were the directions of interest and speed data from these directions were analyzed in this study. Data points removed from this process were about 5.7%, 2.7%, and 12.5% of all observations at Sites 1, 2, and 3 respectively.

At Site 1, stop/slow traffic controls were located upstream of Points 2 and 3 during normal working hours. A careful examination of the data revealed that the first few vehicles in some stop/slow phases did not complete the acceleration process when starting from a stop position, as indicated by increasing speeds of consecutive observations. Since these drivers did not reach their desired speed of travel when passing the tubes, it was necessary to remove those data points (7.8% of remaining data points). The final datasets include 83,156 (Site 1), 169,824 (Site 2), and 298,450 (Site 3) observations.

5. RESULTS

5.1 Descriptive statistics

The collected speed data was first analyzed descriptively, in order to understand the general characteristics of speed profiles at the four locations in the work zones. The descriptive statistics of the speed profiles and magnitude of compliance with posted limits for the three work zones (Sites 1-3) are presented in the Table 1. It should be noted that the statistics were calculated for the directions of interest only (northbound in Site 1 and 2 and westbound in Site 3). Some points in Site 1 (point 3) and Site 3 (points 2, 3, and 4) had different speed limits during the day and night hours, so the statistics were presented separately for the speed limits. In order to determine if the speeds during night-time and daytime are different for a particular combination of work zone, measurement point, and speed limit, a two-sample t-test was employed for each of the combinations. Results of the t-tests are also presented in Table 1 by highlighting the results significant at 99% confidence level using bold faced numbers.

At all three sites, average speeds at Point 1 (after the first speed reduction sign) were higher than the posted speed limits. Compared to Points 2-4, the percentages of vehicles exceeding speed limits (both with small and large margins) were higher at Point 1. This indicates that motorists generally speed more in the upstream work zone areas.

Before the activity area at Site 3, there were two speed limit reductions: first to 80 km/h from 100 km/h at Point 1, and then to 60 km/h (day hours) or to 70 km/h (night hours) at Point 2. Comparison of the speeds at points after the reduced limits revealed that the average speeds were similar, regardless of the changed speed limits. In terms of proportion of vehicles speeding, about 83% exceeded the posted limit at Point 1, whereas almost all (about 97%) vehicles exceeded the limits at Point 2. These results suggest that the speed reduction signage in upstream work zone areas may have very limited effects on travel speeds.

At the start of the activity area (Point 3), the average speeds were higher than the posted speed limits at Sites 2 and 3, with 89% and 72% of vehicles speeding, respectively. However, at Site 1 the Point 3 average speeds were higher than the posted limit when the limit was 40 km/h and lower when the limit was 60 km/h. In addition, the percentage of non-compliant vehicles was much higher under the 40 km/h limit than the 60 km/h limit (66.4% vs. 8.8%). The average daytime speed was higher than at night, with greater difference under a 60 km/h limit (8.5 km/h) than under a 40 km/h limit (3.6 km/h).

Table 1 Descriptive statistics of speed profiles and speed limit compliance

Work zone	Point	No of obs.	Posted speed limit	Mean Speed (km/h)	S.D.	% vehicles speeding	% speeding by at least 5 km/h	% speeding by at least 20 km/h	Mean speed difference (Night-Day) ^a	Mean speed difference (99% CI)
Site 1	1	23906	60	68.4	14.2	76.6	61.6	18.9	8.5	(8.0, 9.0)
Site 1	2	22141	60	50.1	11.7	19.4	11.4	1.7	13.3	(12.9, 13.7)
Site 1	*3	11725	40	43.5	8.2	66.4	44.2	1.7	-3.6	(-4.8, -2.5)
Site 1	*3	6302	60	44.7	10.9	8.8	2.9	0.1	-8.5	(-9.2, -7.9)
Site 1	4	19082	60	49.2	7.7	6.8	1.8	0.1	4.4	(4.1, 4.7)
Site 2	1	53085	60	74.7	8.6	95.5	88.2	25.4	5.6	(5.3, 5.8)
Site 2	3	58858	40	49.1	7.6	89.2	73.5	6.1	4.7	(4.5, 4.9)
Site 2	4	57881	60	59.4	7.4	48.4	18.5	0.5	5.4	(5.1, 5.6)
Site 3	1	79149	80	89.4	10.3	83.2	67.4	14.5	0.5	(0.3, 0.7)
Site 3	*2	48612	60	86.3	13.0	97.6	95.3	72.5	-	-
Site 3	*2	14796	70	89.0	11.2	96.9	90.4	44.7	-1.1	(-1.9, -0.3)
Site 3	*3	62199	60	67.7	14.2	72.7	59.8	18.6	-	-
Site 3	*3	18108	70	76.3	14.2	71.9	55.8	15.4	0.6	(-0.4, 1.6)
Site 3	*4	58532	60	70.9	12.2	84.4	70.9	21.2	-	-
Site 3	*4	17054	70	79.2	11.2	79.6	62.4	16.9	0.4	(-0.4, 1.2)

* Points with different speed limits during day and night periods, - No observation during night-time, **Bold values:** significant at 99% confidence level, ^a H₀: diff (mean night - mean day) = 0 with H_a: diff>0 (if diff is positive) or H_a: diff<0 (if diff is negative)

At the end of activity area (Point 4), the average speed was higher than the posted speed limit at Site 3, but was lower at Site 1 and about equal at Site 2. About 80% of vehicles exceeded the limits at Site 3, whereas only 6.8% did so at Site 1. Although the average speed was almost equal to the posted limit at Site 2, about half of the vehicles still violated the posted speed limit, but mostly by small margins (18.5% had margins of 5 km/h or more). The night-time speeds were significantly higher than the daytime speeds at Site 1 (4.4 km/h) and Site 2 (5.4 km/h).

The average speed measured at a location downstream of a stop/slow traffic controller (Point 2) at Site 1 was lower than the posted limit of 60 km/h. However, 19% of vehicles were exceeding the limit with 11% exceeding by at least 5 km/h and 1.7% exceeding by at least 20 km/h. The average speed during night hours was significantly higher than during daytime. Furthermore, the difference between night and day speeds was higher here than at the other measurement points at this work zone. These findings might imply that motorists drive at lower speeds when passing a traffic controller standing on road, particularly during the day hours. While it is difficult to test with the available data, drivers' difficulty in noticing traffic controllers during night hours might have contributed to the higher night-time speeds.

5.2 Regression model estimates

The parameters of the formulated Tobit model were derived using the Maximum Likelihood Estimation method in the software STATA 11.2. The explanatory variables were examined for potential correlations among variable pairs and those showing high correlations were removed from the dataset. For example, the posted limits of Site 2 and 3 were correlated with the speed measurement points, so were removed from the variable list. To test the robustness of the modeling technique for analyzing speed data from different traffic and roadway

conditions, separate models were estimated for each of the three work zones. It is worthy to note that the three work zones varied significantly in terms of traffic characteristics (average volumes were 3,415, 7,584, and 11,307 vehicles per day at Site 1, 2, and 3, respectively).

The summary statistics of the variables included in the models and the estimates of the model parameters along with their statistical significance are presented in Tables 2 and 3 respectively. Computed values for the change in the expected values of excess speed (amount of speed over the posted limit) for cases with positive values and the change in the probability of a driver's speed being above the posted speed limit (expressed as percentage values) are presented in Table 4. Maddala Pseudo R^2 values of the fitted Site 1 model, Site 2 model, and Site 3 model (0.52, 0.56, and 0.43 respectively) indicate good fit of the models. The corresponding likelihood ratio statistics of the models are 61,256 (25 *df*), 137,836 (24 *df*), and 169,269 (26 *df*) respectively, which are well above the corresponding critical values for significance at 1% significance level, implying that the models have sufficient explanatory power.

Turning to the specific estimation results, relative to the 3-6pm hours, a lower percentage of vehicles were speeding during the other daytime hours (6am-3pm) at both Site 1 and Site 2. Marginal effects of the variables also showed smaller values for both the probability and magnitude of non-compliance during the 6am-3pm period. For example, a driver travelling at Site 1 during 6am-9am had 1.9% lower probability of exceeding the posted speed limit and the speed (if non-compliant with posted limit) is likely to be 0.1 km/h lower than the 3-6pm period. At Site 3, the results for only the 9am-12pm hours were statistically significant. During the early morning hours (12am-3am) all work zones saw higher magnitudes of speeding compared to the 3-6pm period. A driver had 7.3% and 3.5% higher probability of being non-compliant at Site 3 and Site 1 work zones respectively during the 12am-3am hours.

Relative to the end of the activity area (Point 4), the magnitudes of speeding at the other locations (i.e., start and upstream of activity area) were likely to be significantly higher (except at the Point 1 'after first speed reduction sign' location of the Site 3 work zone where the difference was non-significant). The probability that a driver will be non-compliant was highest at Point 1 (after first speed reduction sign), for Site 1 (12.5%) and Site 2 (13.2%), with corresponding increases of 0.95 and 2.50 km/h in the excess speeds (i.e., amount of speed over the posted limit). After passing a stop/slow traffic controller (Point 2, Site 1 only), a driver is 7.0% more likely to exceed the posted speed limit. At the beginning of activity area (Point 3), the probabilities of exceeding speed limits were 2.6% (Site 1), 11.2% (Site 2), and 1.1% (Site 3) higher than those at the end of activity area.

The posted speed limit variable was able to be included in the Site 1 model only, because of collinearity between this variable and the location variable in the other models. Results showed a 25.7% lower probability of observing a vehicle being non-compliant and 2.1 km/h reduction in excess speed under a 60 km/h limit in comparison with a 40 km/h limit.

Table 2 Summary statistics of variables included in Tobit model

Variable	Description	Site 1		Site 2		Site 3	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
<i>Dependent variable</i>							
Excess speed above posted limit		4.35	7.84	8.82	8.17	13.79	11.75
<i>Continuous Independent variables</i>							
Traffic volume^	Number of vehicles in traffic stream	53.67	26.69	139.15	54.90	135.91	66.33
Proportion of medium vehicles^	% medium vehicles in traffic stream	8.63	6.10	9.69	3.97	7.70	4.88
Prop. of heavy vehicles^	% heavy vehicles in traffic stream	14.92	14.51	4.27	4.02	8.87	7.33
Prop. of vehicles speeding^	% vehicles speeding in traffic stream	36.84	34.66	77.28	24.45	83.37	18.49
Prop. of vehicles speeding by 20 km/h^	% vehicles speeding by at least 20 km/h in traffic stream	6.10	12.21	10.27	14.29	27.79	25.34
<i>Categorical Independent variables</i>		Count [#]	% Total	Count [#]	% Total	Count [#]	% Total
Time of day							
00:01 - 03:00	If yes = 1, otherwise = 0	2424	2.92	2275	1.34	4675	1.57
03:01 - 06:00	If yes = 1, otherwise = 0	6252	7.52	7823	4.61	11854	3.97
06:01 - 09:00	If yes = 1, otherwise = 0	11440	13.76	38610	22.74	49456	16.57
09:01 - 12:00	If yes = 1, otherwise = 0	15106	18.17	35112	20.68	56552	18.95
12:01 - 15:00	If yes = 1, otherwise = 0	17957	21.59	31256	18.40	58382	19.56
15:01 - 18:00	If yes = 1, otherwise = 0	17327	20.84	37679	22.19	72150	24.17
18:01 - 21:00	If yes = 1, otherwise = 0	8839	10.63	13277	7.82	31563	10.58
21:01 - 24:00	If yes = 1, otherwise = 0	3811	4.58	3792	2.23	13818	4.63
Speed measurement point							
1	If yes = 1, otherwise = 0	23906	28.75	53085	31.26	79149	26.52
2	If yes = 1, otherwise = 0	22141	26.63	NA		63408	21.25
3	If yes = 1, otherwise = 0	18027	21.68	58858	34.66	80307	26.91
4	If yes = 1, otherwise = 0	19082	22.95	57881	34.08	75586	25.33
Posted speed limit	If 60km/h = 1, 40km/h= 0		83156	85.90	NA		
Type of vehicle							
Light vehicle	If yes = 1, otherwise = 0	63544	76.42	146125	86.04	248986	83.43
Medium vehicle	If yes = 1, otherwise = 0	7038	8.46	16454	9.69	22993	7.70
Heavy vehicle	If yes = 1, otherwise = 0	12574	15.12	7245	4.27	26471	8.87
Gap (from front vehicle)~							
<=2 seconds	If yes = 1, otherwise = 0	24585	29.56	67919	39.99	92354	30.94
2.1 - 4 seconds	If yes = 1, otherwise = 0	26908	32.36	42387	24.96	61013	20.44
4.1 - 8 seconds	If yes = 1, otherwise = 0	10784	12.97	17981	10.59	57007	19.10
8.1 - 14 seconds	If yes = 1, otherwise = 0	5131	6.17	12762	7.51	37269	12.49
>14 seconds	If yes = 1, otherwise = 0	15748	18.94	28775	16.94	50807	17.02
Type of vehicle in front							
Light vehicle	If yes = 1, otherwise = 0	63594	76.48	146124	86.04	248987	83.43
Medium vehicle	If yes = 1, otherwise = 0	7035	8.46	16454	9.69	22992	7.70
Heavy vehicle	If yes = 1, otherwise = 0	12527	15.06	7246	4.27	26471	8.87
Order of vehicle in platoon							
No platoon	If yes = 1, otherwise = 0	41218	49.57	73423	43.23	178373	59.77
Platoon leader	If yes = 1, otherwise = 0	8810	10.59	20831	12.27	31328	10.50
2 nd -5 th in platoon	If yes = 1, otherwise = 0	22779	27.39	52745	31.06	69105	23.15
6 th and beyond	If yes = 1, otherwise = 0	10349	12.45	22825	13.44	19644	6.58
Lane	If right lane= 1, else = 0	NA		NA		298450	79.01

[#] Count of 1 in each category, ~ categorised by starting with the commonly prescribed gap value when following another vehicle (2 seconds) and increasing with increased intervals of the values (safety is expected to vary in greater extent for change in small gap values than that in large values), [^] measured in 15 minute block around the time when a vehicle's speed is measured, NA Not applicable

Table 3 Tobit regression estimates

Explanatory variables	Site 1			Site 2			Site 3		
	Beta	99% CI		Beta	99% CI		Beta	99% CI	
Time of day									
00:01 - 03:00	0.947	0.110	1.785	0.561	0.137	0.985	0.406	-0.073	0.885
03:01 - 06:00	0.449	-0.141	1.039	-0.089	-0.331	0.152	0.046	-0.283	0.374
06:01 - 09:00	-0.543	-0.973	-0.113	-0.484	-0.619	-0.348	0.110	-0.060	0.280
09:01 - 12:00	-0.540	-0.919	-0.161	-0.520	-0.662	-0.379	-0.130	-0.297	0.037
12:01 - 15:00	-0.370	-0.732	-0.008	-0.140	-0.287	0.008	-0.091	-0.251	0.069
15:01 - 18:00	a			a			a		
18:01 - 21:00	-0.192	-0.686	0.302	-0.570	-0.780	-0.361	-0.102	-0.345	0.142
21:01 - 24:00	0.073	-0.627	0.773	-0.423	-0.769	-0.078	0.003	-0.332	0.339
Speed measurement point									
1	3.489	2.863	4.114	3.855	3.580	4.129	0.107	-0.094	0.307
2	2.019	1.544	2.494	NA			0.434	0.171	0.697
3	0.770	0.053	1.487	3.048	2.838	3.258	0.612	0.465	0.759
4	a			a			a		
Posted speed limit		-6.640	-7.400	-5.879	b			b	
Type of vehicle									
Light vehicle	a			a			a		
Medium vehicle	-2.407	-2.840	-1.974	-0.832	-0.983	-0.680	-0.544	-0.732	-0.355
Heavy vehicle	-3.205	-3.558	-2.852	-2.011	-2.230	-1.791	-0.825	-1.003	-0.647
Gap (from front vehicle)									
<=2 seconds	a			a			a		
2.1 - 4 seconds	0.512	0.187	0.837	1.927	1.812	2.041	2.402	2.257	2.546
4.1 - 8 seconds	1.330	0.819	1.841	1.910	1.702	2.118	1.688	1.486	1.890
8.1 - 14 seconds	3.399	2.824	3.973	2.368	2.145	2.591	1.447	1.229	1.665
>14 seconds	3.805	3.338	4.272	1.094	0.900	1.288	1.692	1.481	1.903
Type of vehicle in front									
Light vehicle	a			a			a		
Medium vehicle	-1.097	-1.527	-0.667	-0.527	-0.679	-0.376	-0.293	-0.481	-0.105
Heavy vehicle	-0.920	-1.269	-0.571	-1.746	-1.968	-1.525	-0.339	-0.518	-0.161
Order of vehicle in platoon									
No platoon	2.161	1.649	2.672	1.891	1.695	2.087	1.169	0.953	1.385
Platoon leader	a			a			a		
2nd-5th in platoon	-1.183	-1.631	-0.735	-0.931	-1.080	-0.782	-0.610	-0.796	-0.425
6th and beyond	-2.685	-3.240	-2.131	-3.750	-3.933	-3.567	-3.456	-3.711	-3.201
Traffic volume		0.019	0.012	0.025	0.004	0.003	0.006	0.010	0.008
Proportions of medium vehicles	-			-0.011	-0.023	0.001	-		
Prop. of heavy vehicles	-			-			-		
Prop. of vehicles speeding	0.245	0.238	0.252	0.152	0.148	0.157	0.230	0.226	0.235
Prop. of vehicles speeding by 20 km/h	0.170	0.158	0.182	0.181	0.176	0.187	0.236	0.232	0.241
Lane	NA			NA			0.225	0.043	0.406
Constant	-12.446	-13.51	-11.38	-9.487	-9.94	-9.04	-16.541	-17.10	-15.98
Number of observations	83156			169824			298450		
No of left censored obs	50915			41008			52235		
Log-likelihood (at zero)	-164809			-522422			-1049481		
Log-likelihood (model)	-134181			-453504			-964981		
AIC	268416			907059			1930016		
G2	61256	25 df; p<0.001		137836	24 df; p<0.001		169000	25 df; p<0.001	
Maddala Pseudo R2	0.521			0.556			0.432		

^a Reference category, ^b Removed due to correlation, NA Not Applicable, - Not significant at 95% confidence level

Table 4 Marginal effects of estimated Tobit regression parameters

Explanatory variables	Site 1		Site 2		Site 3	
	Expected value sensitivity ^c	Zero sensitivity (%) ^d	Expected value sensitivity ^c	Zero sensitivity (%) ^d	Expected value sensitivity ^c	Zero sensitivity (%) ^d
Time of day						
00:01 - 03:00	0.27	3.52	0.39	1.65	0.29	7.32
03:01 - 06:00	0.12	1.65	-0.06	-0.28	0.03	0.08
06:01 - 09:00	-0.15	-1.95	-0.32	-1.56	0.08	0.20
09:01 - 12:00	-0.15	-1.94	-0.35	-1.68	-0.09	-0.24
12:01 - 15:00	-0.10	-1.33	-0.09	-0.44	-0.06	-0.17
15:01 - 18:00	a		a		a	
18:01 - 21:00	-0.05	-0.70	-0.38	-1.85	-0.07	-0.19
21:01 - 24:00	0.02	0.27	-0.28	-1.36	0.00	0.01
Speed measurement point						
1	0.95	12.53	2.50	13.23	0.07	0.20
2	0.52	6.99	NA		0.30	0.81
3	0.19	2.57	1.92	11.18	0.43	1.13
4	a		a		a	
Posted speed limit	-2.09	-25.69	b		b	
Type of vehicle						
Light vehicle	a		a		a	
Medium vehicle	-0.63	-8.42	-0.54	-2.81	-0.38	-1.03
Heavy vehicle	-0.82	-10.94	-1.26	-7.45	-0.57	-1.58
Gap (from front vehicle)						
<=2 seconds	a		a		a	
2.1 - 4 seconds	0.13	1.74	1.27	6.34	1.66	4.50
4.1 - 8 seconds	0.35	4.63	1.26	6.30	1.15	3.30
8.1 - 14 seconds	0.94	12.44	1.58	7.52	0.98	2.86
>14 seconds	1.07	14.04	0.70	3.85	1.16	3.30
Type of vehicle in front						
Light vehicle	a		a		a	
Medium vehicle	-0.29	-3.88	-0.35	-1.75	-0.20	-0.55
Heavy vehicle	-0.25	-3.27	-1.10	-6.38	-0.24	-0.64
Order of vehicle in platoon						
No platoon	0.61	8.01	1.33	5.22	0.82	2.10
Platoon leader	a		a		a	
2nd-5th in platoon	-0.30	-4.03	-0.60	-3.27	-0.41	-1.22
6th and beyond	-0.65	-8.69	-2.17	-15.98	-2.20	-8.03
Traffic volume	0.01	0.07	0.00	0.01	0.01	0.02
Proportion of medium vehicles	-		-0.01	-0.04	-	
Proportion of heavy vehicles	-		-		-	
Proportion of vehicles speeding	0.07	0.88	0.10	0.50	0.16	0.43
Proportion of vehicles speeding by 20 km/h	0.05	0.61	0.12	0.59	0.16	0.44
Lane	NA		NA		0.16	0.42

^a Reference category, ^b Removed due to correlation, NA Not Applicable, - Not significant at 95% confidence level, ^c Change in the expected value of excess speed (for cases above zero, i.e., speeding cases), ^d Change in the probability of being above zero (i.e., exceeding posted speed limits)

Compared to light vehicles, all work zones observed lower magnitudes and probabilities of non-compliance for medium vehicles (Site 1: 0.6 km/h, 8.4%; Site 2: 0.5 km/h, 2.8%; Site 3: 0.4 km/h, 1.0%) and heavy vehicles (Site 1: 0.8 km/h, 10.9%; Site 2: 1.3 km/h, 7.4%; Site 3: 0.6 km/h, 1.6%). Similar results were found for the effects of types of lead vehicles on the following vehicle's speeds. Compared to a vehicle following a light vehicle, the probability

of the following vehicle being non-compliant was smaller when following a medium vehicle (Site 1: 3.9%; Site 2: 1.8%; Site 3: 0.5%) or following a heavy vehicle (Site 1: 3.3%; Site 2: 6.4%; Site 3: 0.6%). These results demonstrate that the speed of a particular vehicle and the probability of it exceeding the posted limits not only depend on its type but also on the type of vehicle it is following.

The effect of a driver's freedom to travel at his/her desired speed of travel was captured in the models using the gap variable which expresses the time difference between the front wheels of each vehicle and the rear wheels of its leader vehicle at the point of speed measurement. Relative to the vehicles with a small gap to the vehicles in front (≤ 2 seconds which is usually prescribed to drivers as the safe gap value for following another vehicle—see SWOV, 2012 for details), vehicles with larger gaps were more likely to travel at higher speeds and to exceed the posted speed limits. For instance, at Site 1 the probability of being non-compliant was 1.7% higher when the gap was 2.1 to 4 seconds, 4.6% higher when the gap was 4.1 to 8 seconds, 12.4% higher when the gap was 8.1 to 14 seconds, and 14.0% higher when the gap was greater than 14 seconds. The results were consistent among all three work zones studied.

The platoon variable (expressed in four categories in terms of the position of a vehicle in a platoon, if there is one) was included in the models to capture the effects of platoons on travel speeds. A platoon is defined as a group of vehicles (two or more) travelling close to one other with headway (time difference between the passing of the front wheels of two consecutive vehicles over a particular point) of less than or equal to 4 seconds, as used in many studies (e.g., Hajbabaie et al., 2011b; Sun and Benekohal, 2005). The results showed that the effects of platoon rank and travelling outside of a platoon were consistent across all work zones. Relative to the leaders of platoons, the follower vehicles had lower magnitudes and probabilities of non-compliance. The vehicles in a platoon with 2nd to 5th rank (considering the leader of the platoon as ranked 1st) and those in the tails of platoons (ranks 6th and beyond) had lower probabilities of being non-compliant (Site 1: 4.0% and 8.7%; Site 2: 3.3% and 16%; Site 3: 1.2% and 8.0%). On the other hand, vehicles not in a platoon had higher probabilities of being non-compliant (Site 1: 8.0%; Site 2: 5.2%; Site 3: 2.1%) than the leaders of platoons.

The foregoing shows that type of leader vehicle, gap from a leader vehicle, and order of a vehicle in a platoon affects travel speeds of vehicles. Other characteristics of surrounding traffic, such as traffic volume, proportions of different types of vehicles, and proportions of vehicles speeding may also influence travel speeds. These variables were defined in 15 minute blocks around the time when a vehicle's speed was measured. The results showed that a unit increase in traffic volume (number of vehicles in 15 minute period) was associated with an increase in the amount of excess speed and the probability of exceeding posted speed limits by 0.005 km/h and 0.07% (Site 1), 0.003 km/h and 0.01% (Site 2), and 0.007 km/h and 0.02% (Site 3) respectively. The proportion of medium vehicles was found significant for the Site 2 work zone only, which showed that 1% increment in the proportion of medium vehicles in a 15 minute block was associated with a 0.007 km/h decrease in excess speed and a 0.04% decrease in the probability of being non-compliant.

An increase in the proportion of vehicles in surrounding traffic that were exceeding posted speed limits was associated with the increase in speeds and probabilities of exceeding speed limits of other vehicles. Similar results were obtained for an increase in the proportion of vehicles which exceeded the posted limits by a large margin (at least by 20 km/h). For instance, at Site 1 a 1% increase in the proportion of non-compliant vehicles in the

surrounding traffic was associated with 0.9% increase in the probabilities of other vehicles violating the speed limits. The corresponding values for Sites 2 and 3 work zones were 0.5% and 0.4% respectively. In the case of a 1% increase in proportion of vehicles exceeding the posted limits by a margin of 20 km/h or more in the surrounding traffic, the probabilities of others vehicles being non-compliant were increased by 0.6%, 0.6%, and 0.4% for Sites 1, 2 and 3 respectively. These results indicate that a driver's speed at a particular point is significantly influenced by the speed profiles of other drivers travelling through the same point in a short time interval (in this case 15 minutes).

Only Site 3 had two lanes travelling in the same direction. As expected, the speeds in the right lane were higher, with 0.4% higher probability of a vehicle being non-compliant than in the left lane.

6. DISCUSSION

The current study offers important new insights for work zone speed data analysis. The successful application to analyze speed data at three separate work zones with different traffic characteristics in the current study validates the use of the Tobit regression model. All three models produced similar results in demonstrating the influence of surrounding traffic on vehicle speeds. The model showed that a vehicle is more likely to speed in higher traffic volumes, where there are high proportions of other vehicles speeding, and where other vehicles are speeding by a large margin. Vehicles not in a platoon and the leaders of platoon were more likely to speed than those in the middle of a platoon. Independent of platoons, speeding was more likely where larger gaps exist. The estimated regression coefficients and their marginal effects on both the amount of excess speed and the probability of a driver being non-compliant were consistent and of plausible signs across the three work zones studied. Importantly, the modeling technique used is transferrable and may be applied in a wide range of studies to examine vehicle speeds and to evaluate effectiveness of speed-reduction countermeasures, both within work zones and elsewhere in the general road network. In doing before-after studies of speed reduction countermeasures, special considerations need to be given to any potential site-selection effects, as demonstrated by Kuo and Lord (2013).

This study found some new and interesting results about the effects of traffic characteristics on speeds. Motorists' speeds were significantly influenced by the composition and speeding characteristics of surrounding traffic—a finding that supports the argument made earlier in the paper that traffic characteristics need to be included in modeling work zone speeds. The speed of a particular vehicle at a particular point was found to depend both on the traffic immediately ahead and the traffic passing through this point in a short span of time. The findings that the lead vehicle's speed (both in platoon and away from platoon) influences the speed of following vehicles, and that a driver is more likely to speed if the surrounding traffic is speeding, indicate that drivers may feel pressured by vehicles behind them to increase speed and catch the vehicle in front. Similar to the current study, Morgan et al. (2010) also found that the presence of a lead vehicle had a significant effect on reducing speeds of follower vehicles in work zones. Different traffic flow compositions, specifically the mix of vehicle types by day and night, have also been reported to influence vehicle speeds at work zones. Light vehicles were found to speed more than medium and heavy vehicles, as found in some (but not all, for example Haworth et al., 2002) previous research which analyzed speeds by vehicle types (Benekohal et al., 1992; Bham and Mohammadi, 2011; Debnath et al., 2014).

In upstream work zone areas, both the amount of non-compliance (proportion of vehicles speeding) and the magnitude of speeding (amount over the limit) were found to be greatest among all locations studied. Accordingly, as also found in other research (e.g., Benekohal et al., 1992; Brewer et al., 2006), drivers in the current study were relatively more compliant in close proximity to active work areas, indeed where speed limits are lowest and a large proportion of serious and fatal injuries are most likely to occur (FMCSA, 2002; Mohan and Zech, 2005). While the greater compliance is thus somewhat positive, the degree of non-compliance (44-73% exceeded the limits by at least 5 km/h) nonetheless remains a concern.

The current study also found that the presence of a traffic controller had a notable effect in reducing speeds. After passing a traffic controller (Point 2 of Site 1), most vehicles complied with the posted limit and only 20% exceeded the limit on average at this point. However, the difference between day and night speeds was found to be the greatest at this location (after the traffic controller), suggesting a possible issue with reduced visibility of traffic controllers at night.

Compared to upstream areas, speeding was found to be somewhat less prevalent toward the end of work zones. Speeding was most evident at Site 3, at which there are two lanes travelling in the direction of study under normal conditions, compared with only one lane at Sites 1 and 2. This difference may have influenced a greater amount of speeding towards the end of the Site 3 work zone. Wang et al. (2003) have reported substantial initial speed reductions followed by subsequent increases in the advance warning area, before further reductions at the activity area. The current study's Site 3 observation of no speed difference over two speed limit reductions in the advance warning area suggests a similar approach by drivers, whereby they tend to react more upon seeing activity than they do to posted speed limits. As previously reported, drivers tend to navigate work zones at a speed with which they are comfortable, rather than strictly adhering to posted limits (Brewer et al., 2006; Haworth et al., 2002).

Comparing the three work zones in the current study, across the length of each entire work zone, non-compliance was greater at Site 3 than at Sites 1 or 2. As noted above, on approach to the Site 3 activity area, there was no speed difference observed over two speed limit reductions. On exiting the activity area, speeding was again most common and of greatest magnitude at Site 3. One of the major differences between Site 3 and the other sites was that Site 3 was a divided highway with two lanes in each direction whereas the other sites were on two-lane undivided highways. Although traffic volumes were higher at Site 3 than other sites, these volumes were accommodated over 2 lanes. While pre-work speed limits were similar at all three sites, two lanes therefore approached the Site 3 activity area as opposed to one lane at Sites 1 and 2. This may have contributed to the higher speeds and lower compliance at Site 3 through larger gaps and less platoon effects on vehicle speeds.

The findings of the study could be used to inform countermeasure development, modification and deployment. In particular, targeted enforcement may draw on the findings to identify work zone areas where speeding is most prevalent. Comprehensive examination of platoon effects and gap characteristics assists in achieving improved understanding of speed-related work zone crash causes, including rear-end crashes which are a prominent crash type (Debnath et al., 2013; Hajbabaie et al., 2011b; Sun and Benekohal, 2005). However, a question for countermeasure deployment is whether to target areas where the probability and magnitude of speeding is greatest, where crashes and injury are most likely to occur, or both,

bearing in mind that these areas do not necessarily coincide. The possibility that countermeasure deployment and greater compliance upstream of an activity area will also have significant downstream effects (Medina et al., 2009) should be considered in this regard. In addition to highlighting the prevalence of speeding in particular work zone areas, other specific situations in which vehicles are more or less likely to speed, such as time of day for example, are also could be useful for targeted enforcement.

This study was limited to illustration of the modeling technique in examining speed limit non-compliance at long-term work zones on national highways. Care should be taken when transferring the findings to other contexts, including short-term work zones and urban roads with relatively low pre-work speed limits for example. From an analysis of driver casualty risk in different types of work zones, Weng and Meng (2011) showed that the risk factors (e.g., day of week, gender of driver) have different effects on casualty risk for different types of work zones. The modeling technique illustrated in this paper could however effectively be applied to speed limit compliance modeling in any types of work zones. In using the modeling technique, future work zone speed modeling should focus on three important issues (1) analyzing the effects of driver characteristics on speeds (Weng and Meng, 2012 showed that driver characteristics have significant effects on risky driving behavior including speeding), (2) investigating if work zone geometric characteristics have significant influences on speeds, and (3) examining the potential correlations among speeds of same vehicles measured at different locations. Investigating the second issue is possible by conducting a large scale study involving many work zones of different geometric configuration (e.g., lane width, lane closure, taper length, horizontal and vertical alignment etc.). However, examining the first issue would require conducting a designed experiment in which individual drivers are identifiable in the speed dataset (possibly using a driving simulator). To investigate the third issue—whether the speeds of same vehicles at different locations are temporally correlated—it is necessary to collect some form of vehicle IDs with speed data so that speeds of each vehicle can be tracked. However, this was not possible to do in the current study, because pneumatic tube counters were used to collect speed data. While these counters do not collect any vehicle IDs, they are capable of collecting speed and gap data of all vehicles (so it was possible to identify the platoons and examine their effects on speed limit compliance). It is to be noted that the extensions of the current paper proposed here would require significant data collection efforts which were beyond the scope of the current study. The scope was essentially limited to demonstrating the applicability and validity of the Tobit modeling technique for advancing the methodological development in analyzing work zone speed data.

7. CONCLUSIONS

This paper presented a new technique for modeling speed limit compliance in work zones to understand the how different vehicle and traffic related factors influence speed limit compliance. The technique, which is capable of accounting for both the probability and magnitude of non-compliance, was illustrated using speed data obtained from three long-term highway work zones in Australia. Modeling estimates across the fitted models for the three work zones were consistent and of plausible sign which supports the appropriateness and validity of the modeling technique.

The results showed that motorists' speeds are significantly influenced by the composition and speeding characteristics of surrounding traffic—a finding which highlights the importance of accounting for the effects of vehicle and traffic characteristics in speed limit compliance analysis—which was also a hypothesis behind developing the modeling technique. Light

vehicles and those following a light vehicle, vehicles with larger gaps from leader vehicle, leaders of platoons and those not in a platoon had higher probabilities of being non-compliant with larger margins above the posted speed limits. Higher traffic volumes and higher proportions of non-compliant vehicles in the surrounding traffic were also associated with a higher likelihood and magnitude of non-compliance. Motorists generally speed more in the upstream work zone areas than in the activity area, and upstream speed reduction signage may have limited effects on speed choice. Significant rates of speeding were observed at the start of activity areas, but speeding was found to be less prevalent toward the end of activity area in comparison with other parts of work zones. Motorists were generally compliant when passing a stop/slow traffic controller, particularly during the day. Reduced visibility of traffic controllers during night-time may have contributed to the significant difference between the day and night speeds at this location.

Apart from understanding work zone speed profiles, the modeling technique developed has potential for use in evaluations of the effectiveness of speed-control measures in work zones or in other segments of a road network. Incorporation of driver and work zone geometric characteristics in the modeling framework to understand how these characteristics affect motorists' speed choice would be a valuable addition in future research.

ACKNOWLEDGEMENTS

The authors are grateful to Australian Research Council, GHD Pty Ltd, Leighton Contractors, and QLD Department of Transport and Main Roads for funding the research project titled "Integrating Technological and Organisational Approaches to Enhance the Safety of Roadworkers" (Grant No. LP100200038). The authors would also like to acknowledge the support of the Australian Workers Union. Special thanks go to Mr Colin Edmonston of Transport and Main Roads for his kind assistance in facilitating data collection. The comments expressed in this paper are those of the authors and do not necessarily represent the policies of these organizations.

REFERENCES

- Aarts, L., van Schagen, I., 2006. Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention* 38 (2), 215-224.
- Allpress, J.A., Leland Jr, L.S., 2010. Reducing traffic speed within roadwork sites using obtrusive perceptual countermeasures. *Accident Analysis & Prevention* 42 (2), 377-383.
- Bai, Y., Finger, K., Li, Y., 2010. Analyzing motorists' responses to temporary signage in highway work zones. *Safety Science* 48 (2), 215-221.
- Bai, Y., Li, Y., 2011. Determining the drivers' acceptance of EFTCD in highway work zones. *Accident Analysis & Prevention* 43 (3), 762-768.
- Benekohal, R.F., Hajbabaie, A., Medina, J.C., Wang, M., Chitturi, M.V., 2010. Speed photo-radar enforcement evaluation in Illinois work zones. Report No. FHWA-ICT-10-064, Illinois Center for Transportation, Urbana.
- Benekohal, R.F., Wang, L., Orloski, R.L., Kastel, L.M., 1992. Speed Reduction Profiles of Vehicles in a Highway Construction Zone. Report No. FHWA/IL/UI-241, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana-Champaign.
- Bham, G.H., Mohammadi, M.A., 2011. Evaluation of work zone speed limits: An objective and subjective analysis of work zones in Missouri. Report No. MATC REPORT #25-1121-0001-119, Min-America Transportation Centre, Lincoln.

- Brewer, M.A., Pesti, G., Schneider, W., 2006. Improving compliance with work zone speed limits: Effectiveness of selected devices. *Transportation Research Record* 1948, 67-76.
- Daniel, J., Dixon, K., Jared, D., 2000. Analysis of fatal crashes in Georgia work zone. *Transportation Research Record* 1715, 18-23.
- Debnath, A.K., Blackman, R., Haworth, N., 2013. Understanding worker perceptions of common incidents at roadworks in Queensland. In: *Proceedings of the 2013 Australasian Road Safety Research, Policing & Education Conference*, Brisbane, Australia.
- Debnath, A.K., Blackman, R.A., Haworth, N., 2014. Effectiveness of pilot car operations in reducing speeds in a long-term rural highway work zone. In: *Proceedings of the Transportation Research Board Annual Meeting 2014*, Washington, DC.
- Debnath, A.K., Blackman, R.A., Haworth, N.L., 2012. A review of the effectiveness of speed control measures in roadwork zones. In: *Proceedings of the Occupational Safety in Transport Conference*, Gold Coast, Australia.
- FHWA, 2009. Manual on uniform traffic control devices for streets and highways. In: *Federal Highway Administration, U.S.D.O.T. ed.*, Washington D.C.
- FMCSA, 2002. 2000 Work Zone Traffic Crash Facts. *Federal Motor Carrier Safety Administration*, Washington D.C.
- Garber, N.J., Zhao, M., 2002. Crash characteristics at work zones. Report No. FHWA/VTRC 02-R12, Virginia Transportation Research Council, Charlottesville.
- Hajbabaie, A., Medina, J.C., Wang, M.-H., Benekohal, R.F., Chitturi, M., 2011a. Sustained and Halo Effects of Various Speed Reduction Treatments in Highway Work Zones. *Transportation Research Record* 2265, 116-126.
- Hajbabaie, A., Ramezani, H., Benekohal, R.F., 2011b. Speed Photo Enforcement Effects on Headways in Work Zones. In: *Proceedings of the Transportation and Development Institute Congress 2011*, pp. 1226-1234.
- Haworth, N., Symmons, M., Mulvihill, C., 2002. Safety of small workgroups on roadways. Report No. 195, Monash University Accident Research Centre, Melbourne.
- Kuo, P.-F., Lord, D., 2013. Accounting for site-selection bias in before-after studies for continuous distributions: Characteristics and application using speed data. *Transportation Research Part A* 49, 256-269.
- Li, Y., Bai, Y., 2008. Comparison of characteristics between fatal and injury accidents in the highway construction zones. *Safety Science* 46 (4), 646-660.
- Medina, J.C., Benekohal, R.F., Hajbabaie, A., Wang, M.-H., Chitturi, M.V., 2009. Downstream Effects of Speed Photo-Radar Enforcement and Other Speed Reduction Treatments on Work Zones. *Transportation Research Record* 2107, 24-33.
- Meng, Q., Weng, J., Qu, X., 2010. A probabilistic quantitative risk assessment model for the long-term work zone crashes. *Accident Analysis and Prevention* 42 (6), 1866-1877.
- MetroCount, 2009. Classification Schemes: MTE User Manual. MetroCount.
- Mohan, S., Zech, W.C., 2005. Characteristics of worker accidents on NYSDOT construction projects. *Journal of Safety Research* 36 (4), 353-360.
- Morgan, J.F., Duley, A.R., Hancock, P.A., 2010. Driver responses to differing urban work zone configurations. *Accident Analysis & Prevention* 42 (3), 978-985.
- Queensland Government, 2010. Manual of uniform traffic control devices - Part 3: Works on roads. In: *Department of Transport and Main Roads ed.*, Brisbane.
- Sun, D., Benekohal, R.F., 2005. Analysis of work zone gaps and rear-end collision probability. *Journal of Transportation and Statistics* 8 (2), 71-86.
- SWOV, 2012. Headway times and road safety: SWOV Fact sheet. SWOV Institute for Road Safety Research, Leidschendam, the Netherlands.

- Tobin, J., 1958. Estimation of relationships for limited dependent variables. *Econometrica* 26 (1), 24-36.
- Wang, C., Dixon, K.K., Jared, D., 2003. Evaluation of Speed Reduction Strategies for Highway Work Zones. In: *Proceedings of the 82nd Annual Meeting of the Transportation Research Board*, Washington, D.C.
- Washington, S.P., Karlaftis, M.G., Mannering, F.L., 2011. *Statistical and econometric methods for transportation data analysis* (second edition) CRC Press, Chapman and Hall.
- Weng, J., Meng, Q., 2011. Analysis of driver casualty risk for different work zone types. *Accident Analysis and Prevention* 43 (5), 1811-1817.
- Weng, J., Meng, Q., 2012. Effects of environment, vehicle and driver characteristics on risky driving behavior at work zones. *Safety Science* 50 (4), 1034-1042.